

Quantum Degenerate Mixture of Ytterbium and Lithium Atoms

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We have produced a quantum degenerate mixture of fermionic alkali ^6Li and bosonic spin-singlet ^{174}Yb gases. This was achieved using sympathetic cooling of lithium atoms by evaporatively cooled ytterbium atoms in a far-off-resonant optical dipole trap. We observe co-existence of Bose condensed ($T/T_c \simeq 0.8$) ^{174}Yb with 2.3×10^4 atoms and Fermi degenerate ($T/T_F \simeq 0.3$) ^6Li with 1.2×10^4 atoms. Quasipure Bose-Einstein condensates of up to 3×10^4 ^{174}Yb atoms can be produced in single-species experiments. Our results mark a significant step toward studies of few and many-body physics with mixtures of alkali and alkaline-earth-like atoms, and for the production of paramagnetic polar molecules in the quantum regime. Our methods also establish a convenient scheme for producing quantum degenerate ytterbium atoms in a 1064nm optical dipole trap.

Quantum degenerate elemental mixtures can be used to study a variety of few- and many-body phenomena, and form the starting point for creating quantum degenerate dipolar molecules. While bi-alkali quantum mixtures [1–6] have been produced and studied for about a decade, mixtures of alkali and electron spin-singlet atoms are a more recent development [7–11]. By exploiting the difference in mass of the components, the lithium-ytterbium quantum degenerate mixture may be used to investigate a range of interesting scientific directions including new Efimov states [12, 13], impurity probes of the Fermi superfluid [6], and mass imbalanced Cooper-pairs [14–16]. Furthermore, unlike the bi-alkali case, mixtures of alkali and alkaline-earth-like atoms can lead to the realization of paramagnetic polar molecules by combining the atoms through field-induced scattering resonances. Such molecules hold great promise for quantum simulation and topological quantum computing applications [17]. They may also be good candidates for sensitive tests of fundamental symmetries, particularly if one of the constituents is a heavy atom, such as Yb [18].

In this paper, we report on simultaneous quantum degeneracy in a mixture of alkali and alkaline-earth-like atoms. In earlier work [11], we reported on collisional stability and sympathetic cooling in the ^6Li - ^{174}Yb system, together with a measurement of the interspecies s -wave scattering length magnitude. Here we establish a convenient method to produce Bose-Einstein condensates (BEC) of ^{174}Yb . This allows the sympathetic cooling of ^6Li to well below its Fermi temperature and the achievement of simultaneous quantum degeneracy in the two species.

The cooling of various isotopes of ytterbium to quantum degeneracy has been pioneered by the group of Y. Takahashi in Kyoto [19–21]. In these studies, the optical dipole trap (ODT) was implemented at the wavelength 532 nm. While suitable for confining ytterbium which has a strong transition at 399 nm, this choice of wavelength will not confine common alkali atoms due to their strong transitions occurring at wavelengths greater than 532 nm. For our ODT, we use 1064 nm light arranged in a straightforward horizontal geometry, and demonstrate

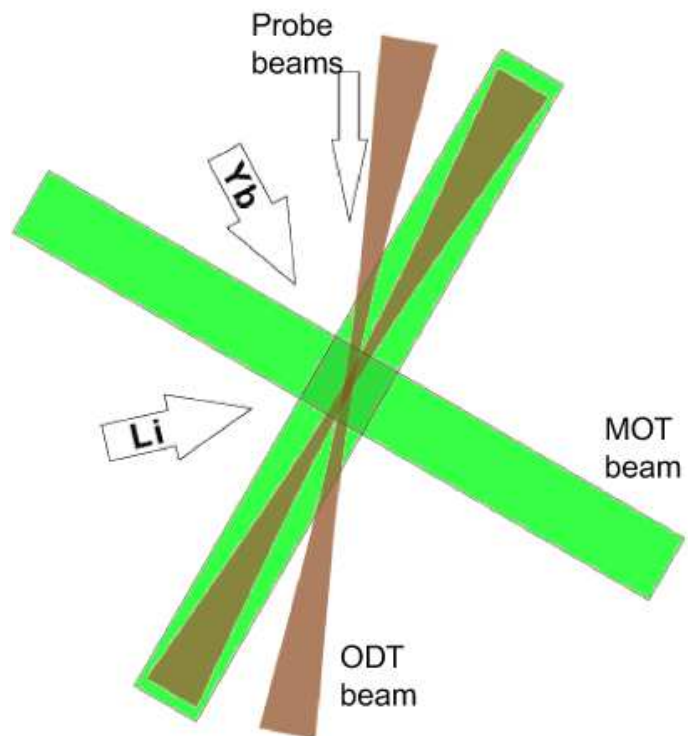


FIG. 1: (color online). Experimental arrangement (top view) for producing simultaneous quantum degeneracy in lithium and ytterbium. Zeeman slowed atomic beams of each species propagate along separate axes towards the MOT. The horizontal ODT beams (brown) are crossed at the MOT region at an angle of 20° . MOT beams (green) for both species are overlapped and arranged in retroreflection configuration. Beams for the vertical MOT axis and Zeeman slowing are omitted in the figure for clarity.

efficient evaporative cooling of ^{174}Yb to BEC. This establishes a simple setup for studies with quantum degenerate ytterbium gases, particularly in the context of dual-species experiments.

Our experimental setup (see Fig.1) is similar to what has been described previously [11]. Briefly, we sequentially load ^{174}Yb and then ^6Li from respective magneto-optical traps (MOTs) into the same ODT. We then per-

form forced evaporative cooling of ^{174}Yb by lowering the power in the ODT. This leads to quantum degeneracy in either single or dual-species experiments. Two improvements to our earlier setup which are crucial for this work are the use of higher power in the Yb Zeeman slowing beam resulting in larger MOT numbers, and the implementation of a tighter ODT geometry [22] leading to more efficient evaporative cooling.

The ODT is derived from a 1064nm linearly polarized fiber laser, operated at a power of 45 W. In order to control the trap depth, the output of the laser is sent through an acousto-optic modulator. The first order output is split into two equal parts with orthogonal linear polarizations which then propagate horizontally toward the atoms. Each beam is focused to a (measured) waist of $26\mu\text{m}$ and the foci are overlapped at an angle of 20 degrees. The trapping potential is characterized through measurements of trap frequencies by parametric heating. The relative trap depths and frequencies for the two species are $U_{\text{Li}}/U_{\text{Yb}} = 2.2$ and $\omega_{\text{Li}}/\omega_{\text{Yb}} = 8.2$. To monitor atom number and temperature, we quickly switch off the ODT and perform resonant absorption imaging of both species.

In single-species experiments with ^{174}Yb , we load 1.5×10^7 atoms in a MOT in 40s from a Zeeman-slowed atomic beam. We use 100mW power in the 399nm ($^1S_0 \rightarrow ^1P_1$) slowing beam and a total of 12mW power in the 556nm ($^1S_0 \rightarrow ^3P_1$) MOT beams, operated in retro-reflection configuration. A transient cooling and compression scheme then produces an atomic cloud at a temperature of $20\mu\text{K}$ containing $\simeq 6 \times 10^6$ atoms.

About 1×10^6 atoms in the 1S_0 state are then loaded into the ODT where the background 1/e lifetime is 40s. The initial ODT power at the atoms is 9 W per beam, corresponding to a trap depth of $430\mu\text{K}$. The power is then reduced by a factor of 100 over a time scale of 14s, utilizing two stages of approximately exponential shape. The first stage lasts for 5s with time constant 1.5s. The second stage lasts for the remainder of the evaporation period and has a time constant of 3.6s.

We observe efficient evaporative cooling with this arrangement (see Fig.2(a)). The critical temperature for Bose-Einstein condensation is achieved after evaporating for $\simeq 12.5\text{s}$. At this point the atom number is $N_{\text{Yb}} = 7 \times 10^4$ and the temperature is $T_{\text{Yb}} = 170\text{nK}$. By fitting to the data prior to condensation, we extract an evaporation efficiency parameter $-d(\ln(\rho_{\text{Yb}}))/d(\ln(N_{\text{Yb}})) = 3.4(4)$ where ρ_{Yb} is the phase space density. Nearly pure condensates of up to 3×10^4 atoms can be prepared by continuing the evaporation process (see Fig.2(b)).

For two-species experiments, we add to the optically trapped ^{174}Yb an equal mixture of the two $F = 1/2$ Zeeman states of ^6Li with an adjustable total number. After 1s of interspecies thermalization at constant trap depth, we perform sympathetic cooling of ^6Li by ^{174}Yb at near-zero magnetic field by using the same evaporation ramp as described above. Sympathetic cooling works well in this mixture as described in our earlier work [11] with the

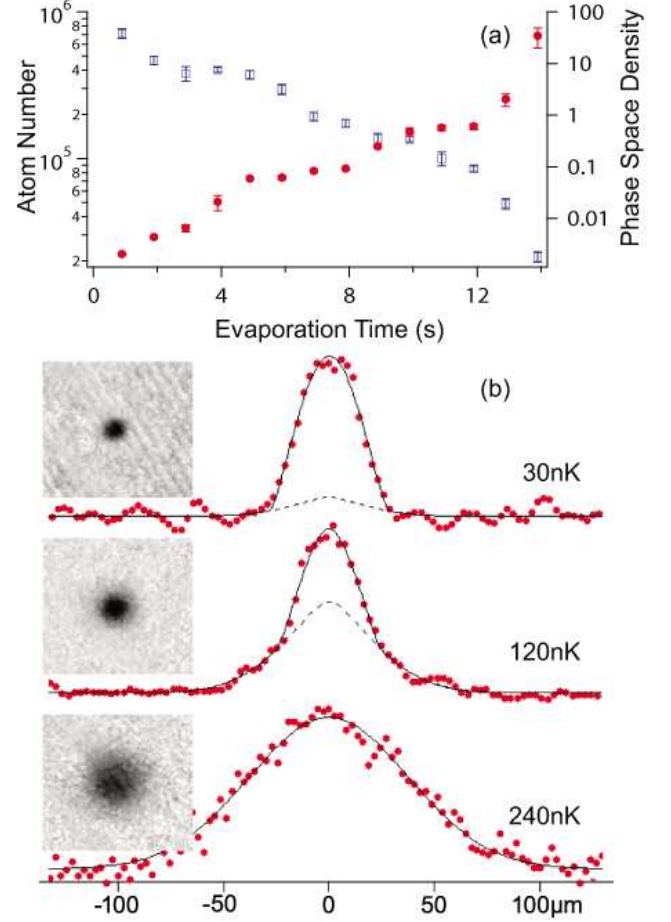


FIG. 2: (color online). Evaporative cooling of ^{174}Yb to Bose-Einstein condensation in the crossed 1064nm ODT. (a) shows the evolution of ^{174}Yb number (open squares) and phase space density (filled circles) for a single-species experiment. BEC is achieved after about 12.5s. (b) shows absorption images and the corresponding atomic density profiles (vertical cross-sections of these images) for three different final trap depths, showing the formation of the BEC. The solid line in each plot is a bimodal fit to the distribution with the dashed line showing the thermal component of the fit. The free expansion time after turning off the trap is 8ms for each image. The total atom numbers and temperatures are $(8.0, 5.6, 2.1) \times 10^4$ and (240, 120, 30) nK respectively.

^6Li number remaining nearly constant due to its greater trap depth. After approximately 14s of evaporation we observe simultaneous quantum degeneracy in the two species (see Fig. 3). At this point the geometric mean trap frequencies are $\bar{\omega}_{\text{Yb(Li)}} = 2\pi \times 90(740)\text{Hz}$, atom numbers are $N_{\text{Yb(Li)}} = 2.3(1.2) \times 10^4$, and temperatures are $T_{\text{Yb(Li)}} = 100(320)\text{nK}$. Here N_{Li} is the total lithium atom number distributed equally between the two spin states. The difference in temperature between the two species is largely attributable to the relative center-of-mass displacement at the end of the evaporation ramp arising from gravitational sag. Assuming perfect over-

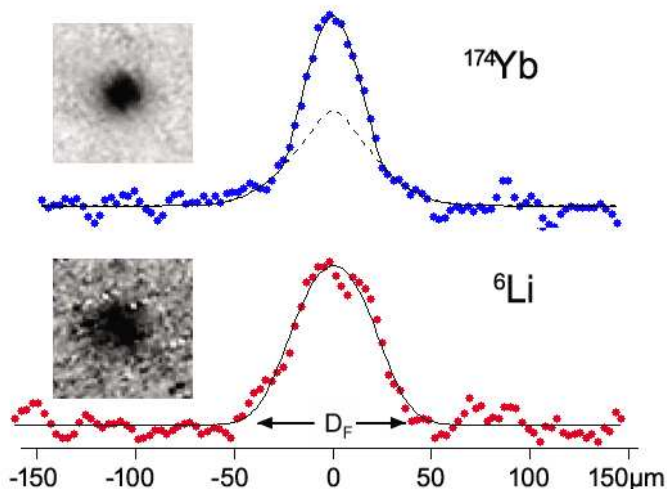


FIG. 3: (color online). Quantum degenerate mixture of ^{174}Yb and ^6Li . The absorption images and density profiles correspond to the same experimental iteration with 14 s of evaporation. The free-expansion times are 8 ms for Yb and 0.7 ms for Li. Here $N_{\text{Yb}} = 2.3 \times 10^4$ and $T_{\text{Yb}} = 100$ nK, corresponding to $T_{\text{Yb}}/T_{\text{C,Yb}} = 0.8$, while $N_{\text{Li}} = 1.2 \times 10^4$ and $T_{\text{Li}} = 320$ nK, corresponding to $T_{\text{Li}}/T_{\text{F,Li}} = 0.3$. For ^{174}Yb , the solid line is a bimodal fit with the dashed line showing the thermal component of the fit. For ^6Li , the solid line is a Thomas-Fermi fit. The extent of the momentum-space Fermi diameter D_F , corresponding to the Fermi energy, is also indicated in the figure.

lap, the estimated interspecies thermalization time at this stage is $\simeq 1$ s, which is reasonably short. However, the separation of the two clouds due to unequal effects of

gravity is $7.5 \mu\text{m}$ while the lithium in-trap Fermi diameter is $11.6 \mu\text{m}$ in the vertical direction. It is therefore not surprising that sympathetic cooling becomes inefficient towards the end of evaporation.

Our results establish a new quantum system comprised of simultaneously degenerate one- and two-electron atomic gases. We also demonstrate a new method for achieving Bose-Einstein condensation of ^{174}Yb using a straightforward horizontal optical trapping arrangement with 1064 nm laser beams. Our setup could also be suitable for combining Yb with other alkalis such as Cs and Rb, since the trap depth and relative sizes would be amenable for sympathetic cooling by ytterbium. Further improvements to our cooling scheme include independent control over the powers in the two ODT beams and an additional magnetic field gradient to improve spatial overlap of the two species.

Extending our method to incorporate alternate ytterbium isotopes (such as the fermion ^{173}Yb [20]) appears realistic. This would then realize Fermi degenerate mixtures with a large mass ratio. Finally, our results represent a significant milestone toward the production of quantum gases of paramagnetic polar molecules. Theoretical work on the LiYb molecule has already been initiated by several groups [23–25]. Future experimental work on our system includes photoassociative spectroscopies and searches for Feshbach resonances [26] in this mixture, key steps towards forming the molecule.

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